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Valuing Sustainability of Open Plan Buildings: A Case Study

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Abstract: The architecture literature acknowledges building adaptability as a means of contributing to sustainability, but falls short in valuation of this contribution. The paper demonstrates how to value sustainability of Open Plan (OP) buildings, where adaptability is deliberately incorporated in the floor plan design with future refurbishment in mind. The literature is reviewed to clarify the notion of OP building as a form of built-in adaptability and to highlight the lack of sustainability valuation of OP buildings. A case study on refurbishment of a university school building is conducted to value the adaptability. A comparative analysis of OP (built-in) adaptability and conventional (non-built-in) adaptability is carried out. Options analysis is utilized for financial valuation, in conjunction with life cycle analysis addressing social and environmental issues. The results show that the OP design is financially viable for early adaptations; and that the inclusion of environmental and social criteria in analysis improves the viability. However, the results cannot be generalized and each situation requires an individual analysis. The paper demonstrates the analysis approach and guides construction practitioners and researchers on how to value adaptable floor plans.

Keywords: Open plan, buildings, refurbishment, adaptation, adaptability, sustainability

1. Introduction

Buildings accommodate social needs through providing residential, office or commercial spaces, and require massive outlay constituting a large portion of people's assets. Changing demands in terms of user preferences trigger changes in building space requirements and adaptations in the forms of additions, alterations or conversions (Kendall, 1999; Moffatt & Russell, 2001; Till & Schneider, 2005). *Additions* imply new construction for expanding building footprint due to increased demand. On the contrary, reductions may involve subletting the space or demolition in part, as a result of decreasing demand (Andersen et al., 2019). *Interiors alterations* indicate changes in space layout by, for example, switching between closed individual spaces and loose spaces, or eliminating inactive areas such as corridors (Attfield, 1999; Till & Schneider, 2005; Herthogs, 2019). This adaptation is basically intended to maximize the usage efficiency of the existing space, with minor changes in floor plan (Attfield, 1999). *Conversions* in use usually occur in response to declining demands, also referred to as adaptive reuse (Thornton, 2011; Manewa et al., 2016). Examples include: preserving heritage buildings (Langston et al., 2013) or converting redundant offices into apartments (Gann & Barlow, 1996; Wilkinson et al., 2009; Remøy et al., 2011). In Australia, about a fifth of construction work has been done on existing buildings to avoid obsolescence (Wilkinson et al., 2009). Also, enormous investment is predicted to be made in construction of new buildings, which can be equipped with built-in adaptability to facilitate easier and cheaper refurbishments.

Building adaptations also cause environmental and social issues associated with resource consumption as well as disruption to building operation, raising a significant sustainability issue. As a result, deliberate adaptability has been introduced with the aim of enhancing sustainability (Gann & Barlow, 1996; Carmichael & Taheriattar, 2018). The

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adaptability refers to a capability (embedded in technical design) to change in line with future circumstances, where knowledge on the change is unclear at the time of design and construction (Slaughter, 2001; Wang & de Neufville, 2005; Gosling et al., 2013; Ross et al., 2016). The architecture literature suggests Open Plan (OP) building as an effective strategy for incorporating adaptability within floor plans.

Floor plans are conventionally designed fit for a single purpose, fulfilling users' needs at the time of design. However, OP buildings allow for adaptations in floor plans (Slaughter, 2001; Schneider & Till, 2005; Wilkinson et al., 2009; Li et al., 2011). Despite the literature acknowledges OP buildings for continuing relevance, there is still a lack of effort to quantitatively value its associated adaptability (Slaughter, 2001; Till & Schneider, 2005; Ladinski, 2017; Rockow et al., 2018). This paper fills the literature gap by valuing OP building adaptability, using a real options analysis for financial valuation (Carmichael et al., 2011), together with life cycle approaches for evaluation of social and environmental intangibles. The valuation is carried out as a comparative analysis between the two forms of adaptation, namely OP design versus conventional design.

First, OP building and its potential contribution to sustainability is further clarified. Then, the sustainability analysis approach is presented on a hypothetical case study involving a school building (at the University of New South Wales) adaptable to a new internal layout is given. However, the paper's methodology is applicable to other situations and locations. People within the building and construction industries will benefit from the paper's approach on viability assessment of OP buildings, with any combination of built-in adaptability features.

2. OP Building: A Built-in Adaptability

Open plan is conventionally used to mean a floor plan of shared, spacious layout with no partitions (Attfield, 1999; Ilozor et al., 2001; Dowling, 2008). Attfield (1999) however mentions that designers have originally seen *open plan as synonymous with free plan providing easy adaptability* (Attfield, 1999, p. 76), for example through spanning large areas with minimal use of internal walls and masonry construction (Herthogs et al., 2019). Schneider and Till (2005) suggest using perimeter load-bearing elements with fixed wet-areas, leaving the remaining space free for variety of layouts configured by light, non-loadbearing partitions. Design for disassembly or modular construction has also been emphasized as a means of incorporating OP adaptability in architecture, facilitating easier alterations (Slaughter, 2001; Engel & Browning, 2008; Ahmed & Aziz, 2019).

Dowling (2008) adds that *open plan is a softer space valued for its functionality as much as its form* (Dowling, 2008, p. 537). Accordingly, Moffatt and Russell (2001) introduce convertibility in use as well as flexibility in space planning for incorporating OP adaptability. Thus, OP design may accommodate multi-functional use of spaces to meet the changing needs (Arge, 2005; Li et al., 2011). This can be realized through designing OP buildings with indeterminate spaces, which are built but not yet equipped till the changing needs necessitate so (Till & Schneider, 2005).

The term OP building, as used in this paper, entails all above approaches and strategies. OP design here refers to a floor plan with deliberate built-in adaptability, capable of changing in line with changed future circumstances.

3. Sustainability and OP Building

Adaptability through OP building can prevent major refurbishments and reduce the associated costs and social and environmental issues such as disruption to building operation or use of resources (Moffatt & Russell, 2001; Langston et al., 2013).

There exist post-refurbishment or operation-related sustainability issues associated with switching between space layouts. For example, an integrated space reduces energy use through utilization of natural lighting and thermal energy, and improves social interactions between users (Shahzad et al., 2016). Or, a multi-cellular layout improves users' privacy and thermal comfort as well as indoor air quality (Saari et al., 2006; Shahzad et al., 2016; Le et al., 2018). However, such issues are not considered in this paper, since they are equally affected by the two adaptation forms compared in the case study. The adaptation forms differ in the quantity and type of physical work involved in refurbishment activities. Thus, the relevant environmental issues include (Larsson, 1999; Moffatt & Russell, 2001; Le et al., 2018): *Resource consumption* – materials and energy use. *Emissions* – equipment-producing emissions; embodied emissions within materials used or demolished. *Waste generation* – material waste and reuse in deconstruction and construction.

OP design typically takes advantage of modular construction, leading to the reuse of building elements and materials during refurbishment. This subsequently reduces the amount of solid waste, materials consumption, embodied energy and emissions (Kats et al., 2003). Such proactive design also accelerates the refurbishment process, leading to further reductions in environmental issues (Gosling et al., 2013; Hong et al., 2014).

Also, the relevant social issues are perceived to include: *Workers* – employment opportunities; health and safety in construction (Sawacha et al., 1999). *Neighbors* – emitted pollutants including dust, noise and vibration; disruption to traffic in the immediate neighborhood (Gilchrist & Allouche, 2005). *Occupants/users* – inconvenience in terms of reduced level of comfort or productivity due to prolonged move-out (Le et al., 2018).

A well-designed OP building may involve more efficient construction methods with less on-site activities, leading to potentially less safety incidents and less disturbance to neighbors and local traffic flow (Gilchrist & Allouche, 2005). The shorter site time also minimizes the inconvenience caused i.e. through minimizing the length of time the occupants have to vacate the building. However, a reduction in total employment is also anticipated due to the shorter site time.

Despite the literature acknowledges OP building as a means to implement adaptability and enhance sustainability, there is still lack of effort to quantitatively value its sustainability, perhaps because of the OP building subjectivity (Moffatt & Russell, 2001; Slaughter, 2001; Till & Schneider, 2005; Manewa et al., 2016; Rockow et al., 2018; Ahmed & Aziz, 2019; Herthogs et al., 2019). A few studies attempted quantification, but using inadequate approaches. Gann and Barlow (1996) talk of open plan floor to facilitate conversion in use and enhance sustainability, but provide no quantitative support. Herthogs et al. (2019) suggest a graph-based method to measure the building adaptability, but not the contribution of adaptability to sustainability. Larsson (1999) and Moffatt and Russell (2001) present preliminary estimates of energy use, emissions and solid waste over the open building's life-cycle to highlight the benefits of increased longevity. Ladinski (2017) conducts a case study to examine the contribution of designing spaces for adaptability, but falls short in placing a value on it. Andersen et al. (2019) evaluates the building refurbishment using a multi-criteria decision making approach, which may be criticized because of the subjectivity of the definition of scales and the allocation of scores. With OP building providing an option (a right but not an obligation) to change floor plans, real options analysis (ROA) should be utilized for financial valuation. The ROA has not been attempted in the OP building literature though. Apparently, the literature also lacks valuation of social and environmental aspects. The case study conducted in this paper fills this literature gap.

4. Analysis: Outline

Two forms of adaptation are considered and compared here, namely adaptation of OP design versus adaptation of Base (conventional) design. In the former, the adaptability features are designed and built in floor plan, with the view that adaptation may (but not necessarily) take place in the future depending on future circumstances. While in the latter, the floor plan is designed and built without adaptability features in mind, but future adaptation may still be fortuitously possible.

OP building adaptability is here valued using the approach presented in Carmichael and Taheriattar (2018). The analysis looks at (OP design) the extra effort of designing in adaptability and the subsequent adaptation, compared with (Base design) the more usual situation of not designing in adaptability and extra effort to adapt.

The options analysis is utilized for financial valuation – only costs at adaptation time, T, are considered. Expected values, E[ ], and variances, Var[ ], of the costs are estimated using optimistic (a), most likely (b) and pessimistic (c) values. This leads to: expected value = (a + 4b + c)/6, and variance = $[(c - a)/6]^2$. Because estimates for both designs are based on similar assumptions, very strong correlation (approximately one) between the estimates is assumed.

To ascertain the value of OP adaptability over conventional practice, the difference between OP and Base is looked at. Let X_T be the net cost at time T. That is,

$$X_T = \mathrm{Base}_T - \mathrm{OP}_T \tag{1}$$

where OP_T and Base_T are the costs, at T, of OP design and Base design, respectively. Then,

$$E[X_T] = E[\mathrm{Base}_T] - E[\mathrm{OP}_T] \tag{2}$$

$$\mathrm{Var}[X_T] = \left(\sqrt{\mathrm{Var}[\mathrm{Base}_T]} - \sqrt{\mathrm{Var}[\mathrm{OP}_T]}\right)^2 \tag{3}$$

These are discounted to give the present worth, PW, of the difference.

$$E[PW] = \frac{E[X_T]}{(1+r)^T} \tag{4}$$

$$\mathrm{Var}[PW] = \frac{\mathrm{Var}[X_T]}{(1+r)^{2T}} \tag{5}$$

where r is the interest rate. Then, the adaptability value is calculated,

$$\text{Adaptability value} = \Phi M \tag{6}$$

where $\Phi = P[PW > 0]$, P is probability, and M is the mean of the present worth upside measured from PW = 0. To calculate Φ and M, and knowing E[PW] and Var[PW], any distribution can be fitted to PW; however, a normal distribution is usually used. The adaptability value is then compared with the cost of incorporating OP adaptability at time 0. Financial viability is established for the OP building when the adaptability value exceeds this initial cost.

Also, the environmental and social issues are evaluated through Life Cycle Assessment (LCA) tools. The process LCA method is used for the assessment of the difference between the OP design and Base design (Benoît et al., 2010; ISO, 2006). The analysis looks at the sustainability issues at times t = 0 and T, assuming no differences between the OP and Base designs at other times. A case study involving OP building adaptability is here analyzed using this approach.

5. Case Study: Civil Engineering Building Refurbishment, UNSW

Australia is regarded as one of the largest providers of international education services, which is gathering momentum. This has resulted in growing demand for building activity in Australian universities. Accordingly, the increasing number of users and changing wants has caused the existing school buildings at UNSW (constructed in early 1960s) to undergo major refurbishments. The Heffron building and Mechanical Engineering building are the examples with substantial refurbishments completed recently. The Civil Engineering (CE) building is very likely to require similar alterations. The CE building is here studied for OP adaptability. As such, the existing conventional floor plan (Base design) is compared against a hypothetical OP design capable of switching to new space layouts. The given approach is applicable to other situations including refurbishment or new builds. It however requires ingenuity and engineering knowledge to identify innovative OP adaptability features.

5.1 Design and Construction

The CE building is a concrete structure building, designed with a central shaft withstanding lateral actions. The typical conventional floor plan involves a central corridor with a string of cellular rooms at one side and a larger room at the other side (Figure 1). The assumption in the following is that the alterations have insignificant impact on the imposed loads, and subsequently on the foundation design. Thus, the main building elements to be considered are the columns, floors and internal walls.

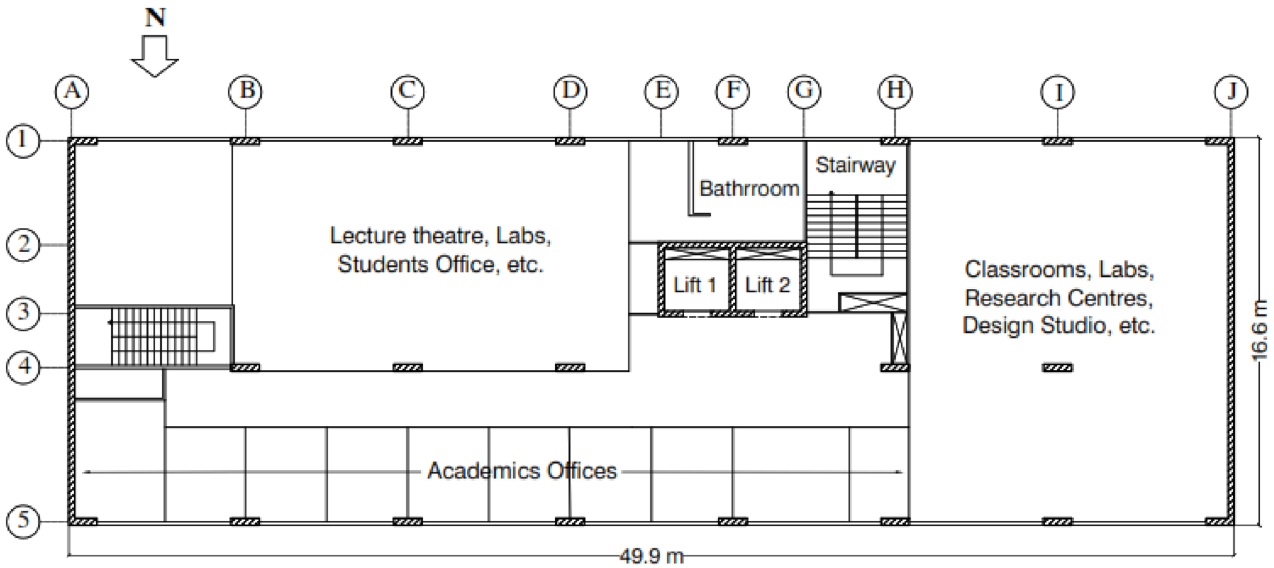

Fig. 1 - Upper levels: typical space layout, t = 0

The CE building refurbishment involves:

1) Creating a more spacious layout at upper levels by capturing corridors for active use as well as relocating the school office from level four to ground level (Figure 2). This is done for both Base and OP designs at time T (adaptation or refurbishment time). As such, the high-demand spaces are placed at lower levels with easier access, while upper levels accommodate quiet spaces. This also reduces unnecessary travels within the building.

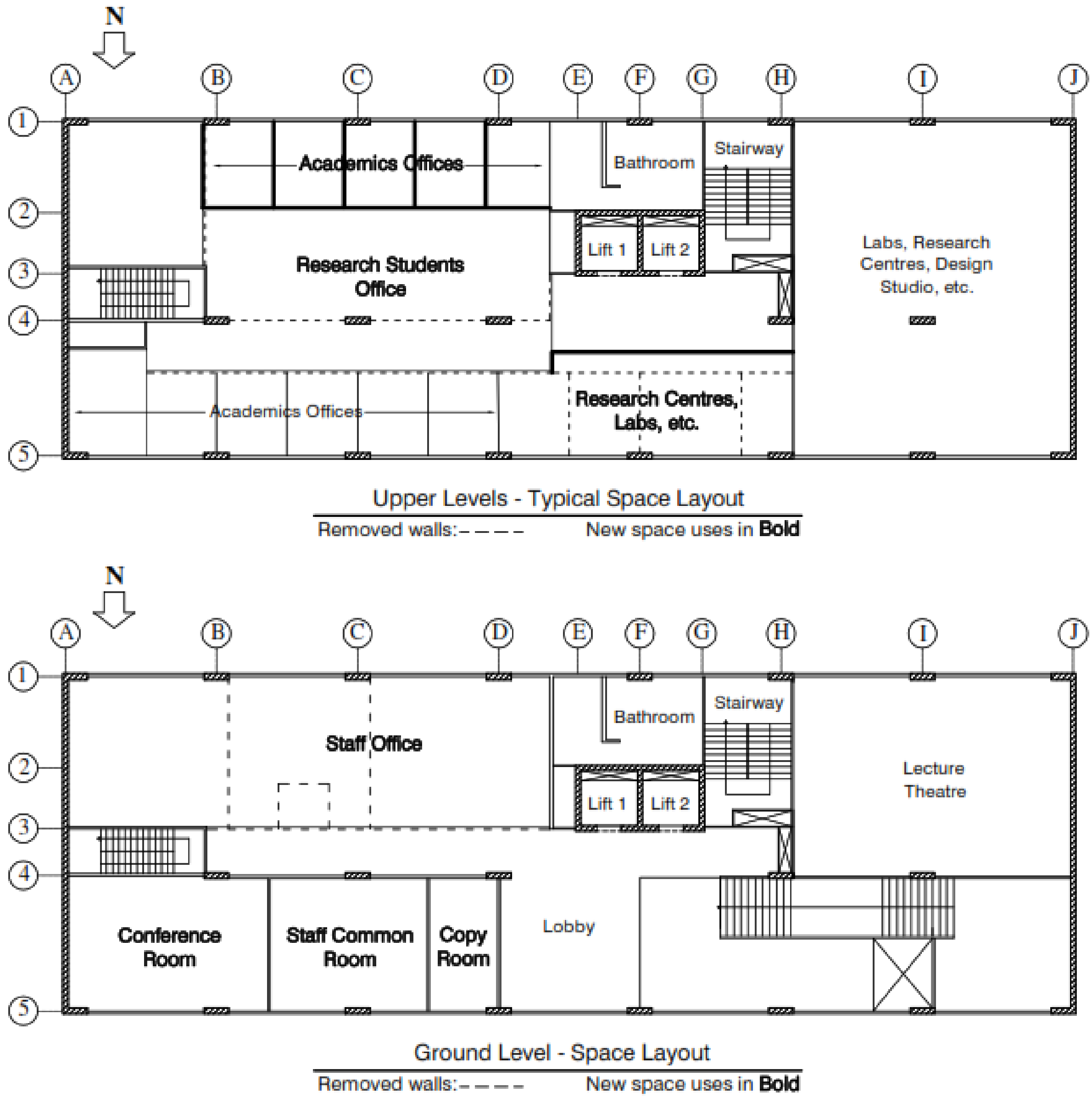

Fig. 2 - Upper levels and ground level: changes in space layout, t = T

2) Developing a new lecture theatre with no obstructive columns. Possible solution for the OP design (as done in Mechanical building) is to combine spaces at two levels such that the slab is demolished and an inclined, raised floor is added (Figure 3). The conventional floor in Base design allows for creating openings into the slab at refurbishment time; but a spandrel beam has to be constructed at the edge of the openings to maintain the structural integrity. The OP design, because of a built-in adaptability feature, allows for building the lecture theatre at one level – just internal walls are relocated. The adaptability features are detailed in the following.

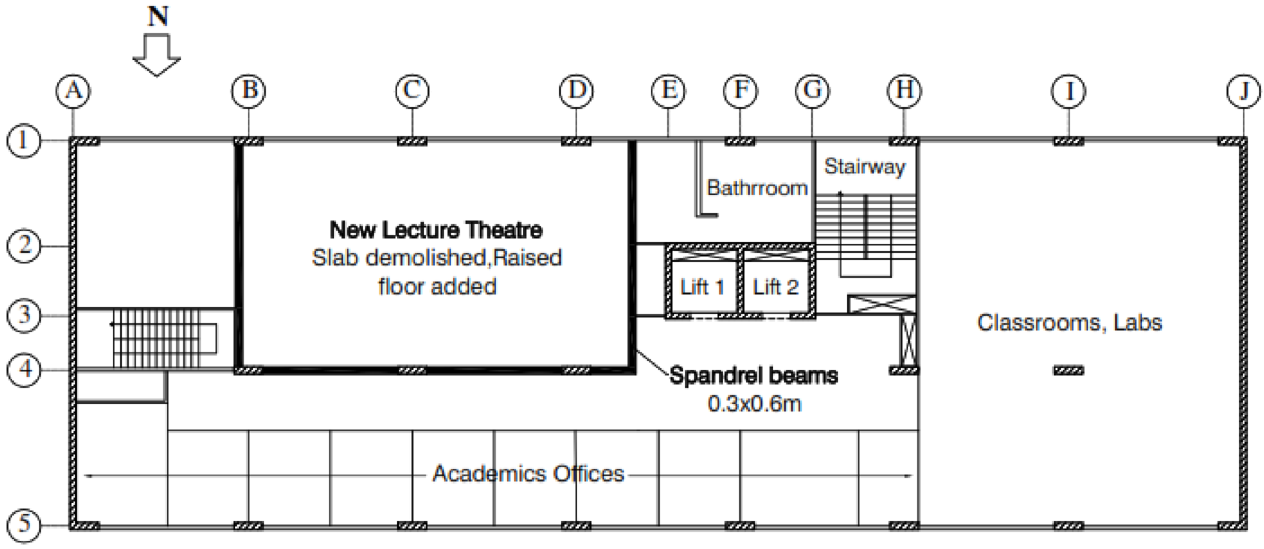

Fig. 3 - Developing a new lecture theatre: Base design, t = T

Columns. In the Base design, the columns are positioned in a two-span structural grid. The possibility for the OP design is that specific interior columns (here, column C4) at lower level be eliminated in initial design (Figure 4). This creates a clear-span space that can be used for a variety of purposes (here, a lecture theatre). As such, the loads from upper level are transferred to the adjacent perimeter columns. Thus, the section design for the two perimeter columns changes from 0.3x1.2m to 0.45x1.4m. There might exist alternative methods such as using composite columns, but not considered here.

Floors. The clear-span design requires changing flooring system above the lecture theatre from traditional slab and beam (0.6m deep) to post-tensioned slab with a transfer beam section of 0.9x1.4m (Figure 4). The transfer slab supports upper interior columns and distributes the associated loads to the lower perimeter columns.

Internal walls. In conventional construction, solid internal walls are built to divide the spaces. While the OP design utilizes modular internal walls with prefabricated panels attached to metal or timber frames. This leads to easier construction and deconstruction of the walls. As well, the modular walls and particularly the supporting frames might be re-assembled and re-used in part (say 50% here) where the walls are relocated for space rearrangement.

Table 1 summarizes the differences between OP and Base designs that are analyzed here. Others may look at building construction differently – the activities and quantities will change, but the valuation methodology will be the same.

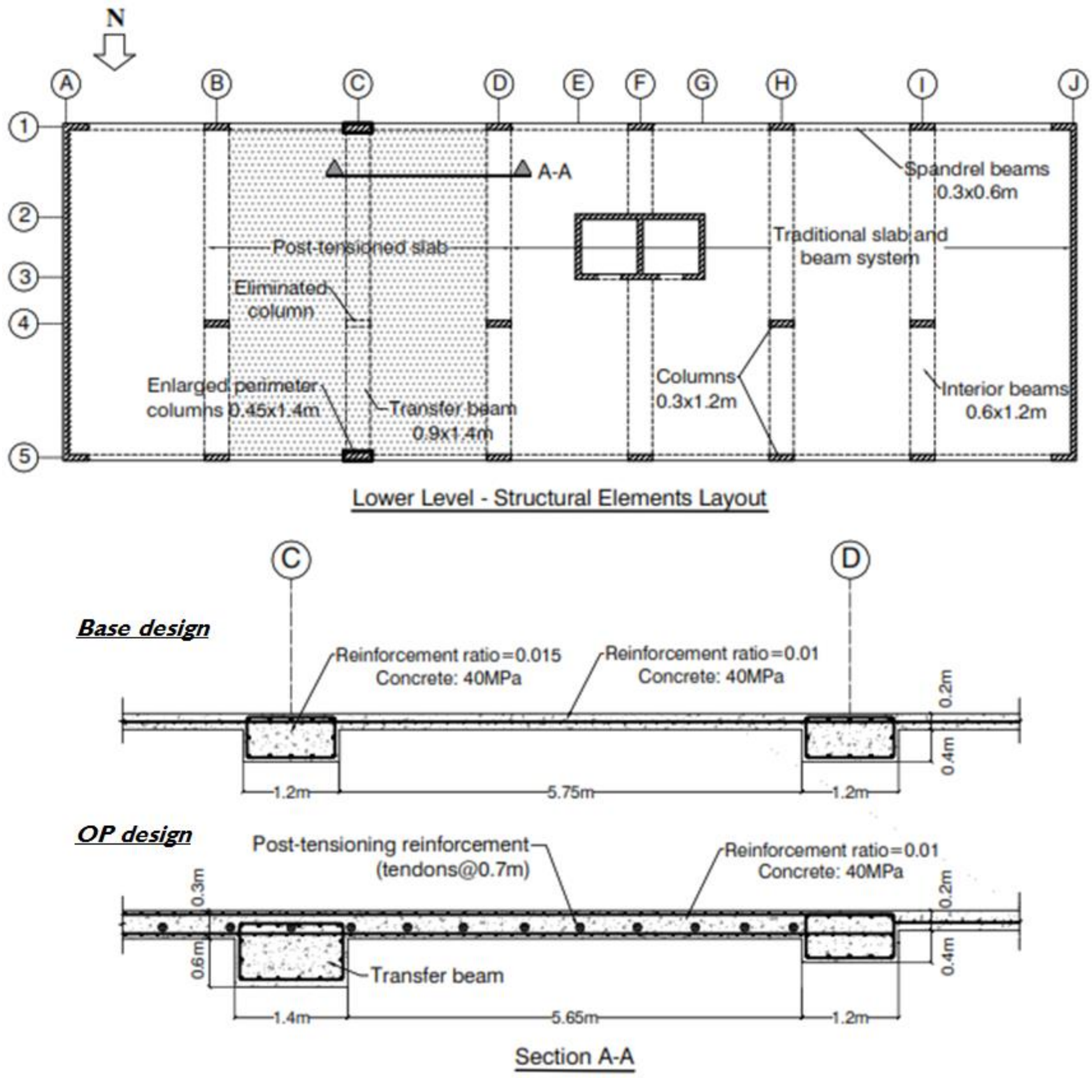

Fig. 4 - Column layouts and flooring systems at lower level – OP vs. Base, t = 0

Table 1 - Differences in activities and quantities – OP vs. Base, t = 0 and T

OP design	Base design
t = 0	
• Build modular internal walls = 820 lm	• Build solid internal walls = 820 lm
• Construct perimeter columns of bigger size = 1.6 m^3	• Construct interior column = 1.1 m^3
• Construct post-tensioned slab and transfer beam = 79 m^3 (1.5 t post-tensioning reinforcement)	• Construct traditional slab and beam system (49 m^3 concrete)
t = T	
• Disassemble internal walls = 428 lm	• Demolish internal walls = 408 lm
• Build new modular walls = 52 lm	• Build modular internal walls = 266 lm
• Reassemble internal walls = 214 lm	
	• Demolish slab in part = 125 m^2
	• Construct spandrel beams = 3.5 m^3
	• Construct raised floor = 140 m^2

5.2 Financial Valuation

Costing estimates follow Rawlinsons (2019) based on the quantity take-offs, together with quotations from industry representatives. Optimistic, most likely and pessimistic estimates of the refurbishment costs at time T are made, leading to expected values and variances of the costs:

$E[Base_T]$ = \$325.9k, $Var[Base_T]$ = (\$27.2k)^2
$E[OP_T]$ = \$102.4k, $Var[OP_T]$ = (\$8.5k)^2

OP adaptability value is then calculated using the analysis formulation given earlier. Figures 5 and 6 show the change in OP adaptability value with r and T. The initial investment in OP adaptability is estimated to be \$89.0k. It is seen that the OP design is only viable for lower r and lower T. If r = 5%, the OP design will be financially more viable than the Base design for the refurbishment time up to 15 years. With lower interest rates, the OP design will be viable even for longer refurbishment times. For example, the interest rate of 2% leads to viability of the OP design for the refurbishment time of 35 years. However, the average time the school buildings undergo major refurbishments ranges between 35 and 50 years. Thus, the university's facility management might not build in OP adaptability and might require an enhanced incentive for investment. The inclusion of the social and environmental intangibles may improve the viability.

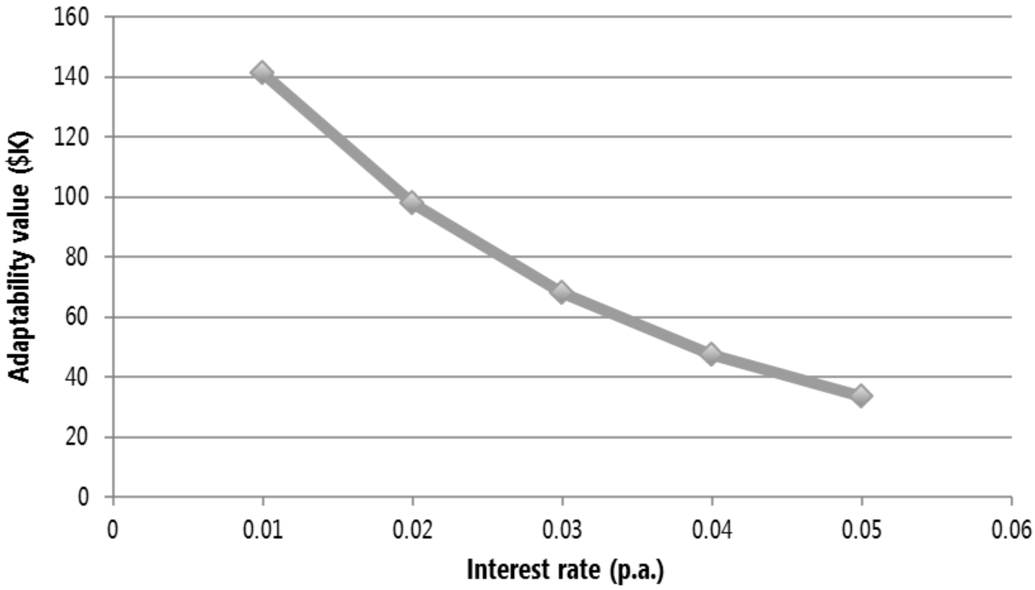

Fig. 5 - Change in OP adaptability value with interest rate (p.a.). T = 35 years

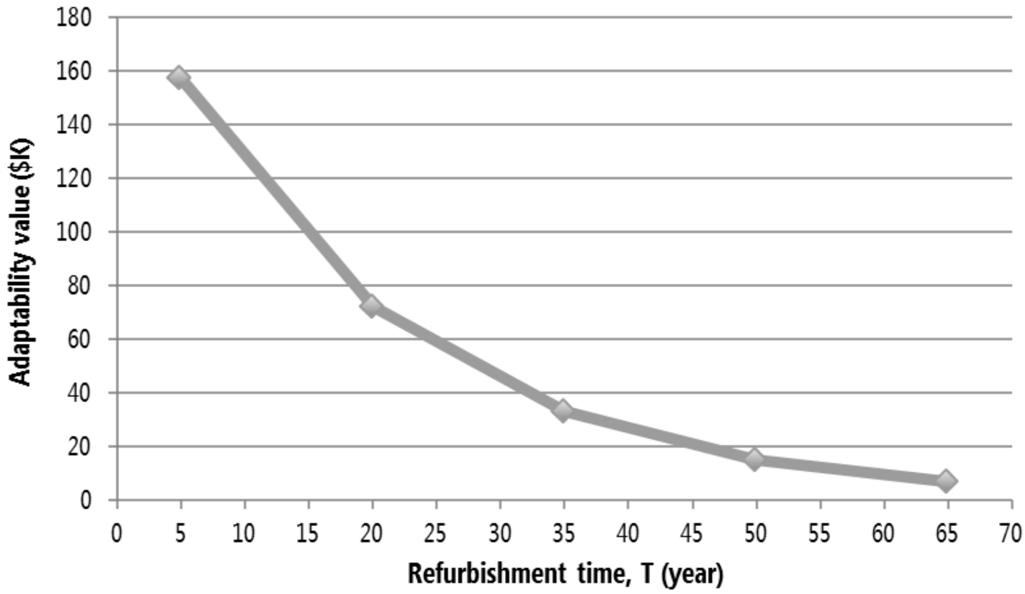

Fig. 6 - Change in OP adaptability value with time of refurbishment T. r = 5% p.a

5.3 Environmental Assessment

Environmental issues that are different between OP and Base designs are noted in Table 2.

Table 2 - Comparison of environmental issues – OP vs. Base, t = 0 and T

OP design	Base design
t = 0	
• Superstructure: more solid waste, more material use, longer construction time – embodied energy, emissions	• Internal walls: more solid waste, more material use, longer construction time – embodied energy, emissions
t = T	
• Internal walls: part reusable – less solid waste, less material use	• Internal walls: longer deconstruction time – more energy use • Superstructure: more solid waste, more material use, longer construction time – embodied energy, emissions

Environmental inventory flows, consisting of materials and energy (environmental inputs) and emissions and solid wastes (environmental outputs), are tracked for the unit processes of construction and deconstruction at times 0 and T. Differences in inventory flows between the OP and Base designs are estimated. Timber, bricks and reinforced concrete are the predominant materials used. Embodied energy and emissions are calculated using the inventory database provided by Hammond and Jones (2011). The effect of longer site time on energy use and emissions is assumed to be included in embodied values. Also, assembling the prefabricated wall frames is assumed with no on-site wastage. The differences in environmental inventory flows are summarized in Table 3 (for further detail on the estimates, see Appendix A).

Table 3 - Differences (OP – Base) in environmental issues

Environmental issue	At t = 0	At t = T	Combined t = 0 and T
Materials consumption (t)	-280	-24	-304
Energy use (GJ)	-556	-165	-21
Emissions (ton CO2-e)	-43	-13	-56
Solid waste production (t)	-18	-312	-330

It is seen that the OP design considerably improves the environmental performance. The OP design performs better with respect to any of the environmental issues; hence, the OP design is environmentally preferable to the Base design regardless of the weighting of the issues. The results also demonstrate that the OP design and the associated adaptability features do not necessarily increase the environmental loadings at t = 0.

5.4 Social Assessment

Social issues that are different between the OP and Base designs are noted in Table 4.

Table 4 - Comparison of social issues – OP vs. Base, t = 0 and T

OP design	Base design
t = 0	
• Superstructure: longer construction time – dust, noise, vibration, neighborhood disturbance, potential for accidents	
• Internal walls: modular construction – noise, vibration, lower paid hours for workers	• Internal walls: longer construction time – dust, neighborhood disturbance, potential for accidents
t = T	
• Shorter deconstruction and construction time – lower paid hours for workers	• Longer deconstruction and construction time – dust, noise, vibration, neighborhood disturbance, potential for accidents, temporary displacement of occupants – productivity reduction

With the same scope and unit processes as those determined for the environmental assessment, the relevant social inventory flows comprise worker employment (social input), safety incidents, health damage and inconvenience (social outputs).

The differences in the social inventory flows between the OP and Base designs are estimated. Worker employment is measured in total worker hours (hours per worker multiplied by number of workers), using RSMeans (2019) data on crew composition and productivity rates. Safety incidents are measured based on a frequency, namely the number of potential injury occurrences per hours worked (AS 1885.1, 1990). Health damage due to exposure to construction noise varies with activity-equivalent-continuous-noise level (in decibels, dB) and number of exposure hours (hours per person multiplied by the number of affected people) (BSI, 2009), and has units of dBh. The predominant activities generating noise include modular wall construction, concrete placing and compaction, brick walls demolition, slab demolition, and raised floor construction. Inconvenience implies disruption to people's everyday life due to construction, measured in total working hours delayed or disrupted. The differences in the social issues are summarized in Table 5 (for estimation detail, see Appendix B).

Table 5 - Differences (OP – Base) in social issues

Social issue	At t = 0	At t = T	Combined t = 0 and T
Worker employment (h)	-4265	-641	-4,906
Safety incidents (number of injuries)	-0.1407	-0.0212	-0.1619
Health (dBh)	81,236	-82,376	-1,140
Inconvenience (h)	-676	-8,694	-9,370

From Table 5, the OP design improves the social sustainability performance by addressing all the issues, except worker employment. The results endorse that the OP design does not necessarily lead to greater social issues at t = 0. Overall, the OP design is seen to perform better than the Base design with respect to the social issues combined.

6. Conclusion

The demand for educational spaces in Australia is increasingly growing, creating the need for refurbishment of existing buildings as well as construction of new OP buildings for future adaptation, subjected to valuation. The literature acknowledges OP building with adaptability in space use as a means to enhance building sustainability, but there is lack of effort to quantify this value. This paper advanced the current literature by performing a quantitative analysis of OP building sustainability using a case study of the refurbishment of a school building. The OP (built-in) adaptability form was compared with the conventional (non-built-in) adaptability form.

The results show that the OP design, compared to the conventional design, is financially viable only for lower interest rates and earlier refurbishment times than the average. From the social and environmental aspects, the OP design is concluded to be preferable. Hence, the inclusion of environmental and social criteria improves the viability and supports arguments in favor of OP building. The results also demonstrate that, unlike the common speculation, incorporating OP adaptability in design does not necessarily cause more environmental or social issues in initial construction. The alleviation of environmental or social issues is mainly due to the modular construction, which reduces resources consumption and site time.

It is believed that university facility managers would apply considerable weighting to the sustainability intangibles, compared to the financial aspects. The Australian universities and UNSW in particular have targeted towards climate change mitigation, seeking ideas for implementation at the university campus. The idea of OP school buildings was shown to be an effective solution with particular emphasis on the reduced energy use and emissions.

However, the results of the case study cannot be generalized to conclude on sustainability of OP design, but rather an individual analysis is required for each situation. The methodology will remain the same, but the design and associated numbers may change. OP building may be worthwhile in some situations, but not necessarily in all situations. The paper demonstrated the OP building valuation using the suggested approach, which will be useful to the building industry and the building owners seeking enhanced sustainability in construction and refurbishment.

Appendix A: Detail of environmental inventory flows (OP vs. Base design) at times 0 and T

Differences at t = 0

Materials

- *OP*: Internal walls – timber and plasterboard consumption of 98 t. Superstructure – additional reinforced concrete of 139 t.
- *Base*: Internal walls – brick consumption of 517 t.

Energy

- *OP*: Internal walls – 827 GJ more embodied energy for materials consumed. Superstructure – 167 GJ more energy use due to differing amount of reinforced concrete.
- *Base*: Internal walls – 1550 GJ for bricks consumed.

Air emissions

- *OP*: Internal walls – 55 ton CO2-e (carbon dioxide equivalent) emissions. Superstructure – 26 ton CO2-e more emissions for additional quantity of reinforced concrete used.
- *Base*: Internal walls – 124 ton CO2-e emissions.

Solid waste

- *OP*: Internal walls – 2 t solid waste i.e. plasterboard. Superstructure – 3 t more solid waste due to extra amount of reinforced concrete used.
- *Base*: Internal walls – 23 t solid waste i.e. bricks.

Differences at t = T

Materials

- *Base*: Internal walls – new materials i.e. timber and plasterboard of 32 t consumed. Superstructure – reinforced concrete of 8.5 t for spandrel beams; timber of 2.5 t for raised floor.
- *OP*: Internal walls – new materials of 19 t consumed (timber of 13 t reused).

Energy

- *Base*: Internal walls – 267 GJ embodied energy for the materials consumed. Superstructure – 10 GJ energy use due to spandrel beams construction; 25 GJ embodied energy for timber consumed in raised floor construction.
- *OP*: Internal walls – 137 GJ embodied energy for the materials consumed.

Air emissions

- *Base*: Internal walls – 18 ton CO2-e embodied emission for the materials consumed. Superstructure – 1.5 ton CO2-e embodied emissions for reinforced concrete; 2 ton CO2-e for timber raised floor.
- *OP*: Internal walls – 8.5 ton CO2-e embodied emission for the materials consumed.

Solid waste

- *Base*: Internal walls – 257 t waste (brick) materials due to demolition; 0.6 t solid waste i.e. plasterboard in new construction. Superstructure – 92.5 t solid waste due to slab demolition; 0.4 t waste materials for construction of spandrel beams; 0.2 t timber waste for raised floor construction.
- *OP*: Internal walls – 38.5 t solid wastes due to deconstruction (given that wall frames of 13 t are reused).

Appendix B: Detail of social inventory flows (OP vs. Base design) at times 0 and T

Differences at t = 0

Worker employment

- *OP:* Internal walls – 832 h. Superstructure – extra 140 h for concrete forming; 200 h for steel fixing; 35 h for concrete placing.
- *Base:* Internal walls – 4640 h.

Safety incident

- *OP*: Potentially 0.1407 more injuries due to the additional 4265 h employment.

Health

- *OP*: Internal walls – 832 worker hours of exposure to equivalent continuous noise of 78 dB due to drilling and screwing. Superstructure – assume 8 workers and 30 people in the vicinity subjected to equivalent continuous noise of 86 dB over the extra 5 h of concrete placing.

Inconvenience

- *Base*: (Assume a traffic flow of 200 persons per hour for the adjacent pedestrian blocked; a 0.1 km longer detour; and average walking speed of 5 km/h). Additional travel delay of 676 h over the extra site time of 169 h (extra 256 h for construction of

Differences at t = T

Worker employment

- *Base*: Internal walls – 736 h for demolition. Superstructure – 120 h for slab demolition. Spandrel beams construction: 60 h for concrete forming; 5 h for steel fixing; 12 h for concrete placing. 60 h for raised floor construction.
- *OP*: Internal walls – 352 h for deconstruction.

Safety incident

- *Base*: Potentially 0.0212 more injuries due to the extra 641 h employment.

Health

- *Base*: Internal walls – 736 worker hours exposed to equivalent continuous noise of 89 dB due to demolition. Superstructure – 120 h of exposure to equivalent noise of 91 dB due to slab demolition. 12 worker hours subjected to equivalent noise of 86 dB during concrete placing for spandrel beams. 60 worker hours exposed to equivalent noise of 82 dB due to carpentry activities during raised floor construction.

Inconvenience

- *Base*: Extra total site time of 161 h (i.e. extra 96 h for removal of internal walls plus additional 65 h for building new lecture theatre i.e. slab demolition, construction of spandrel beams and raised floor). Assume: that same detail for pedestrians flow and detour as used at t = 0; and that 500 occupants having to vacate the building, with 10% productivity reduction in the temporary office.
    - Additional travel delay of 644 h over the longer site time of 161 h.
    - Longer disruption of 8050 h due to productivity reduction over the extra site time.

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